Prognostic Health Management for Avionics System Power Supplies

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Abstract[1]-This paper presents an integrated approach to switching mode power supply health management that implements techniques from engineering disciplines including statistical reliability modeling, damage accumulation models, physics of failure modeling, and sensor-based condition monitoring using automated reasoning algorithms. Novel features extracted from sensed parameters such as temperature, power quality, and efficiency were analyzed using advanced fault detection and damage accumulation algorithms. Using model-based assessments in the absence of fault indications, and updating the model-based assessments with sensed information when it becomes available provides health state awareness at any point in time. Intelligent fusion of this diagnostic information with historical component reliability statistics provides a robust health state awareness as the basis for accurate prognostic predictions. Complementary prognostic techniques including analysis of projected operating conditions by physics-based component aging models, empirical (trending) models, and system level failure progression models will be used to develop verifiable prognostic models. The diagnostic techniques, and prognostic models have been demonstrated through accelerated failure testing of switching mode power supplies.

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1. INTRODUCTION

Electronic systems such as electronic controls, on-board computers, communications, navigation and radar perform many critical functions on-board military and commercial aircraft. All of these systems depend on electrical power supplies for direct current (DC) power at a constant (regulated) voltage to drive solid-state electronics. With these power supplies playing an important role in the operation of aircraft systems and subsystems, flight and ground crews need health state awareness and prediction tools that diagnose faults accurately, predict failures, and project life remaining of these components. A specific goal of the Joint Strike Fighter (JSF) technology maturation programs is to develop health state awareness and prediction capabilities through Prognostics and Health Management (PHM) for all JSF systems including avionics. Substantial safety and cost benefits are projected if the optimal application of LRU diagnostic and prognostic techniques is realized.

Switch-mode power supplies (SMPS's) are commonly used aboard aircraft where their weight, size, and efficiency make them preferable to conventional transformer-based power supplies. In addition to regulating the voltage of direct current (DC) power, these novel circuits can also serve as DC to DC converters that can step down ("bucking" design) voltage like conventional supplies or step up ("boost" or "flyback" design) voltage. However, SMPS's are no panacea. Many early SMPS designs suffered from sudden and catastrophic failures or generated excessive electromagnetic interference (EMI). More recent SMPS designs employ protective circuits to isolate sensitive components from damaging events.

The DC-DC converter at the heart of SMPS's uses a switching element, along with capacitors and inductors, to step up or step down voltage and current accordingly. High

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speed switching enables the transfer of energy packets from the input filter capacitor to the output filter capacitor. The last stage filters out any high frequency components from the DC output. Finally, the output is feedback into a control circuit that stabilizes the DC/DC converter. Figure 1 shows a simplified diagram of a SMPS.

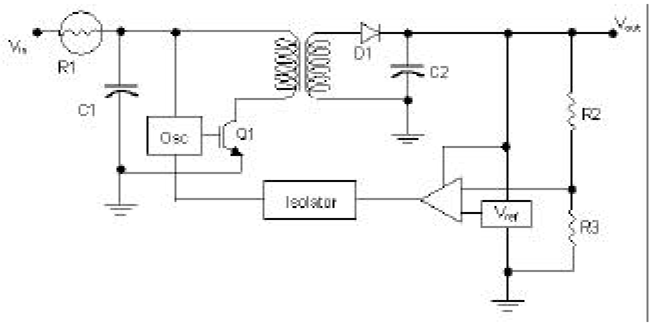


Figure 1 - Simplified Block Diagram of a (boost) SMPS

On the input side of the power supply, an inrush current protection device controls the current charging capacitor C1 when V_{in} is first applied. This device could be a thermistor (R1) as shown in Figure 1 or an active inrush surge limiter. A filter on the input consisting of capacitors (C1) and other components blocks radio frequency interference (RFI) generated by the SMPS from contaminating the input power. The oscillator (OSC) switches the power transistor Q1 with a pulse width modulated (PWM) signal at a frequency around 100 kHz. During each PWM cycle the current through the primary side of the transformer ramps up when Q1 turns on. When Q1 turns off, the voltage applied to C2 rises as the inductor attempts to maintain current on its secondary side and charges C2. The duty cycle of the PWM signal determines the voltage applied to C2, and is set based on feedback (control) from comparison of a fraction of V_{out} with V_{ref}.

2. SMPS FAILURE MODES

Reliability studies of switching mode power supplies have shown that the majority of failures may be attributed to a small number of components (Pareto effect) [i, ii, iii, iv]. The relative frequency of specific component failures may vary based on SMPS topology, type of component used, derating factors, and location in the system. The components that commonly fail are classified into three different categories:

- Switching Transistors
- Filtering Capacitors
- Rectifying Diodes

Three types of switching transistors are commonly used in SMPS applications; bipolar junction transistors (BJTs), metal-oxide semiconductor field-effect transistors (MOSFETs), and insulated-gate biplolar transistors (IGBTs). Each type of transistor exhibits unique failure modes and rates, but switching transistors are generally the leading cause of SMPS failures. Bipolar junction transistors are widely used in SMPS designs where low priorities for weight and efficiency allow lower switching frequencies. MOSFETs and IGBTs are more common in applications where weight and efficiency requirements mandate higher switching frequencies.

The primary purpose of output filter capacitors in a SMPS is to suppress high frequency noise generated by switching in the DC-DC converter. As a consequence, the output filter capacitor is subject to continuous voltage ripples. The magnitude of the voltage ripple is dependent on ESR, ambient temperature, output current, and the input voltage of the converter. [v] Stress is also applied to the capacitor when a load is removed from the power supply. If the control circuit cannot respond fast enough to the event, the energy stored in the inductor transfers to the capacitor, accumulating internal damage [vi].

The two types of filtering capacitors are commonly used in SMPS applications, tantalum capacitors and electrolytic capacitors are both susceptible to failure by dielectric breakdown, though each exhibit type of capacitor has unique root causes of failure. Filtering capacitors are the second largest source of SMPS failures. These capacitors are required to have large capacitance, high voltage ratings, and low equivalent series resistance (ESR). Tantalum capacitors are replacing electrolytic capacitors for their small form factor and higher reliability.

The diodes that are used to rectify the input and output voltage in switching mode power supplies are also a significant cause of failure. Shockley diodes are commonly used in rectifiers. The leading failure modes affecting switching mode power supplies are summarized in Table 1 vii.

Table 1 SMPS Failure Modes

Failure Modes	Related Components	Cause of Failure	Possible Effects	Probability of Occurrence	Criticality	Possible Action to Reduce Failure Rate of Effect
Contact Migration	- BJTs - Diodes	- Electrical overstress - Temperature - High current density	-Decreased efficiency - Increased turn-on resistance	High	Catastrophic	-Improve heat dissipation -Choose a transistor with a higher current rating
Corrosion	- BJTs - Capacitors - Diodes - MOSFETs	- Moisture	- Internal corrosion -Bonding pad corrosion	Low	Marginal	-Operate in an environment with minimal moisture
Dielectric Breakdown	- Capacitors	- Electrical overstress - High operating voltage - Temperature	- Short circuit - Open circuit	High	Catastrophic	- Increase voltage rating - Add a small series resistor
Electromigration	- BJTs - Capacitors - Diodes - MOSFETs	- High current densities - Electrical overstress - Temperature	-Metal interconnect failure	Low	Marginal	- Use a transistor with a higher current rating
Gate Oxide Breakdown	- MOSFETs	- Electrical overstress - Temperature	-Increased threshold voltage - Increased turn-on resistance - Decreased efficiency	High	Catastrophic	- Choose a transistor with a higher current rating
Hot Carrier Effect	- MOSFETs	- Large electric field in the channel region	- Short circuit	Low	Marginal	- Reduce drain-to-source voltage
Thermal Runaway	- BJTs - Diodes - MOSFETs	- Increased operating temperature - Gate Oxide Breakdown	- Short circuit	High	Catastrophic	- Improve heat dissipation
Thermal Cycling	- BJTs - Capacitors - Diodes - MOSFETs	- Environmental temperature cycling - Power up/down cycle	- Thermal runaway	Medium / High	Critical	-Reduce exposure to rapid changes in environmental temperature

Criticality: Marginal Critical Catastrophic

3. PHYSICS OF FAILURE MODELS

Physics of failure models are used as the basis for incipient fault detection, fault to failure progression, and remaining useful life predictions. Critical transistor failure modes include thermal runaway, gate-oxide breakdown, contact migration and thermal fatigue. Thermal runaway and thermal fatigue can affect all types of transistors, while gate-oxide breakdown only affects MOSFETs and contact migration only affects BJTs. Thermal runaway, contact migration, and thermal fatigue also affect diodes. Critical capacitor failure modes include dielectric breakdown and thermal fatigue.

While thermal runaway affects all types of transistors, bipolar junction transistors are the most susceptible due to the positive feedback relationship between device temperature and heat generation. As the temperature of a BJT rises, so does its heat generation. When the rate of heat generation exceeds the capacity of the heat sink, the temperature of the device rises quickly until it fails. Temperature is therefore the primary indicator of thermal runaway. Thermal runaway may occur when a device cannot remove the additional power generated by electrical overstress events or an increase in internal resistance due to gradual device degradation. Thermal runaway eventually leads to a short circuit mode.

Gate oxide breakdown is one of the major concerns regarding metal-oxide semiconductor field effect transistors (MOSFET) devices. Damage to the gate oxide (Figure 2) can result in excessive leakage current, increased standby power, and a decrease in response time. Eventually, the damage will cause a MOSFET to short-circuit. The damage results from thinning of the oxide and an increase in the effective electric field. Two types of gate oxide breakdown are possible: A catastrophic breakdown can occur as the result of electrical overstress. Time-dependent dielectric breakdown (TDDB), takes place during operation within the rated conditions of voltage, temperature, and power dissipation. Time dependent dielectric breakdown refers to the damage accumulated in the gate oxide region of a MOSFET during use within its rated operating condition. The rated operating conditions include voltage, temperature, and the magnitude of the electric field between the drain and body. Both types of gate oxide breakdown ultimately result in a short circuit between the drain and source regions of a MOSFET.

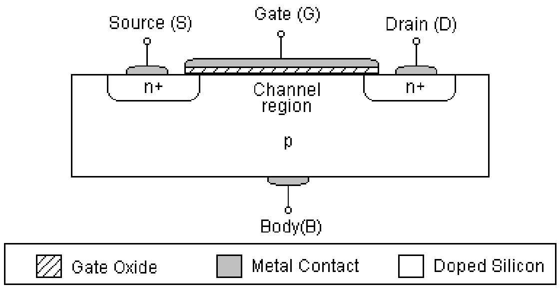


Figure 2 - MOSFET Gate Oxide Channel

Modeling TDDB lifetime depends on the strength of the electric field so long as the oxide region is at least moderately thick. For relatively strong electric field, the expected life (τ_f) is proportional to the reciprocal of the applied electric field strength (Equation 1). In contrast, the expected life in a weak electric field is proportional to the electric field strength (Equation 2).

$$\ln(t_f) \propto \frac{1}{E_{db}} \tag{1}$$

$$\ln(t_f) \propto -E_{db} \tag{2}$$

Contact migration can affect rectifier diodes and BJT switching transistors in a SMPS. Contact migration occurs when material from aluminum contacts diffuses into the silicon region. The diffused aluminum forms "spikes" in the silicon region, which can eventually short out a pn junction as shown in Figure 3. Junction spiking occurs as a result of high current densities resulting from electrical overstress. A model for contact migration is given in Equation 3.

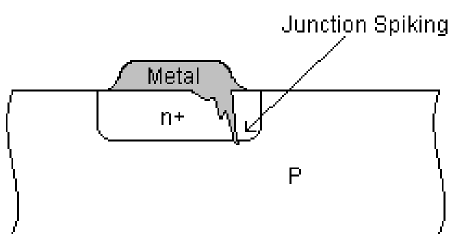


Figure 3 - Contact Migration

$$t_f \propto (J - J_{crit})^{-N} e^{(E_a / kT)} \tag{3}$$

J = Current Density
Ea = Thermal Activation Energy
Jcrit = Critical Current Density
N = Correction factor (1 – 2)

All components in a SMPS, particularly diodes, transistors, and capacitors, are susceptible to thermal fatigue failures. Fatigue damage due to thermal cycling accumulates every time a device experiences a power-up and a power-down cycle and every time a device experiences an environmental temperature cycle. Thermal fatigue eventually weakens metallic contacts and may cause: dielectric film cracking, lifted bonds, solder fatigue, and cracked dies. The Coffin-Manson model is used to estimate the number of thermal cycles till failure, is shown in Equation 4.

$$N_f = C_0 [\Delta T - \Delta T_0]^{-q} \tag{4}$$

N_f = Number of cycles to failure
C_o = A material dependent constant
ΔT = entire temperature cycle-range for the device
ΔT_0 = elastic region temperature cycling
q = an empirically derived constant

Dielectric breakdown can occur in all types of capacitors. When dielectric breakdown occurs, current flows from one side of the capacitor through the insulating layer to the other side of the capacitor. Breakdown occurs differently in electrolytic and tantalum capacitors. Dielectric breakdown occurs gradually in electrolytic capacitors whereas dielectric breakdown occurs abruptly in tantalum capacitors. Temperature, operating voltage, electrical overstress (or current transients) are all parameters that accelerate dielectric breakdown. The results of dielectric breakdown are catastrophic, resulting in either a short circuit or open-circuit failure.

The effects of dielectric breakdown in electrolytic capacitors are catastrophic, but the symptoms develop gradually. A model of a real capacitor includes parasitic elements that cause a capacitor to take on very low resistive and inductive properties, shown in Figure 4. These non-ideal characteristics include some equivalent series resistance (ESR), as well as lead inductance and equivalent parallel resistance (EPR).

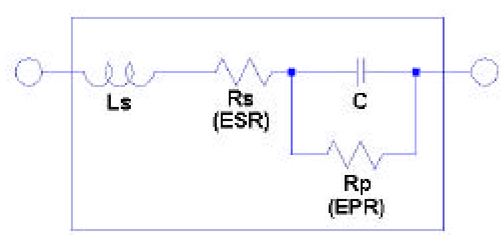


Figure 4 - Model of a real capacitor.

As an electrolytic capacitor ages, the electrolytic fluid begins to evaporate drying out the capacitor and causing an increase in ESR. Since the magnitude of ESR is inversely proportional to the maximum amount of current a capacitor can handle, the internal temperature of the capacitor begins to increase. As the temperature and power dissipation begin to increase, the likelihood of dielectric breakdown occurring increases. As a result of dielectric breakdown, the capacitor enters a short circuit failure mode.

Tantalum capacitors possess a lower failure rate when compared to electrolytic capacitors when operated at the same rated conditions [viii]. The low failure rate of tantalum capacitors is due in part to the annealing process that enables 'self healing'. As faults develop in the dielectric, increased current flow generates heat that promotes the formation of a manganese trioxide patch as shown in figures 5, 6 and 7 respectively.

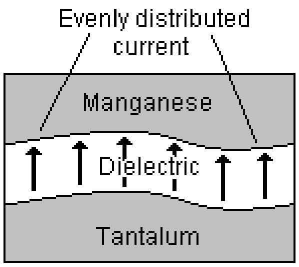


Figure 5 - Cross section of a healthy capacitor

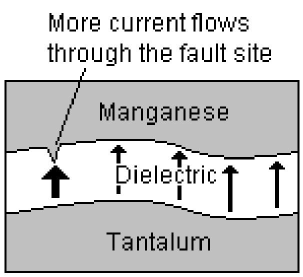


Figure 6 - Cross Section of a Degraded Dielectric

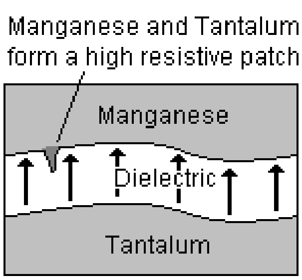


Figure 7 - Cross section of degraded Manganese Dioxide

4. ACCELERATED FAILURE TESTING

The SMPS fault to failure progression models and diagnostic features for incipient fault detection were verified through accelerated failure tests of commercially available computer power supplies. To generate failures quickly, a load emulator shown in Figure 8 was designed and built subject the test specimens to extreme electrical and thermal stress.

The load emulator successfully generated multiple switching transistor and diode failures over the course of three months of testing. While tests designed to generate capacitor failures were performed, no catastrophic capacitor failures occurred.

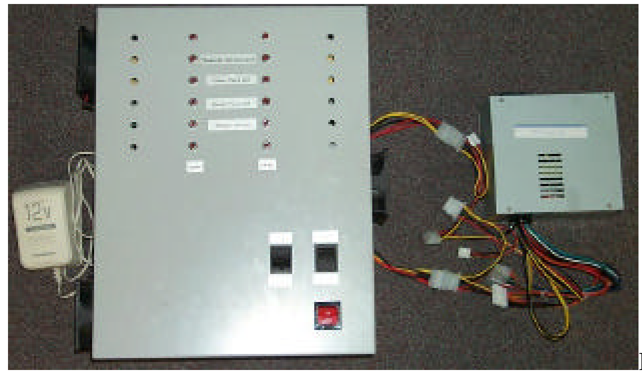


Figure 8 - **Outside View of the Load Emulator**

The bipolar junction transistors in the test supplies exhibited both thermal runaway and contact migration induced failures. As thermal runaway occurs, the temperature of the switching transistor begins to increase exponentially until the semiconductor becomes permanently conductive and the transistor exhibits a "short circuit" failure mode. This failure mode was observed in the lab by attaching a thermocouple to a power transistor in a SMPS. According to the data that was obtained in the lab, thermal runaway began 67 minutes before failure.

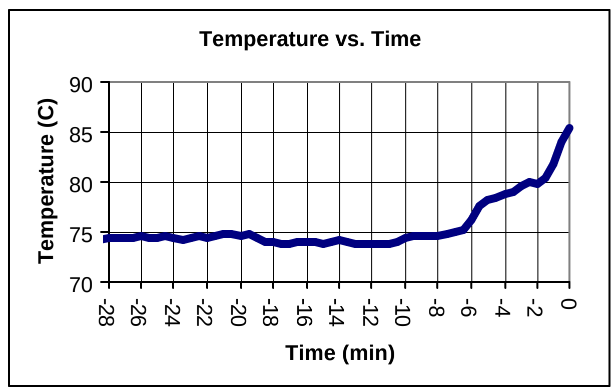


Figure 9 - Transistor Temperature vs. Time During Thermal Runaway

The switching transistors also exhibited failures which are believed to be the result of contact migration. Electrical overstress applied by the load emulator causes metal from contacts to diffuse into the semiconductor. Eventually a junction spike occurs, shorting the two regions together causing a short circuit that allows a high current to flow through the device.

During these accelerated failure tests, the input and output power was monitored for transients that indicate the onset of damage. This is best illustrated in a plot the ratio of output power to input power or efficiency vs. time as shown in Figure 10. An electrical overstress event causes the efficiency to instantaneously decrease by almost 4% around

1240 minutes into the test. The transistor failed 160 minutes later.

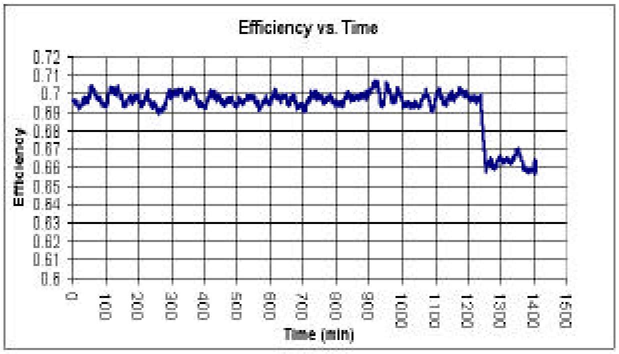


Figure 10 - Efficiency vs. Time During BJT Failure

Destructive examination of the transistor revealed a bond wire failure as shown in Figure 11. These light gauge wires that connect the semiconductor to the external solder connections can fail when subjected to a large current.

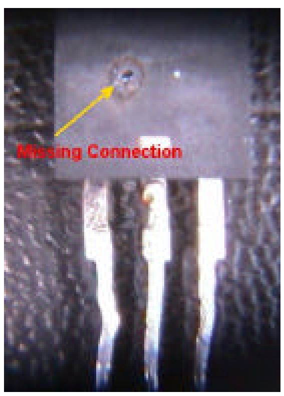
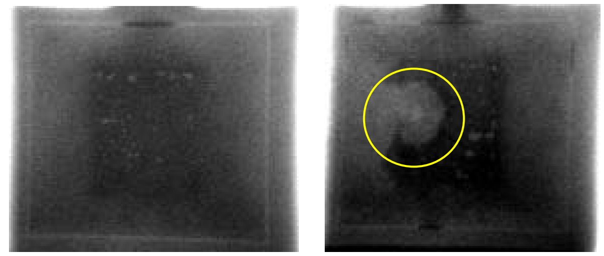


Figure 11 - Failed bond wire

The electrical stress applied by the load emulator also induced a rectifier diode failure. The diode is believed to have failed due to from junction spiking as a result of electromigration. Figure 12 shows x-rays of a healthy (S10C40C) die and the damaged die. The circled area indicates damage to the silicon from a short circuit across a PN junction. This short was most likely cuased by a electromigration induced spiking.



Healthy DIE　　　　　　Damaged DIE

Figure 12 - Xray of a healthy and damaged DIE from a S10C40C Shockley Rectifier

During the same accelerated failure test, the input power, output power, output voltage, output current and efficiency were recorded. Before the failure occurred, the diode was subjected to severe electrical overstress 1250 minutes into the test. After the event, the regulation of the 5V output changed, as shown in Figure 13. Although the power supply was still functioning, it had difficulties keeping the 5V output constant, which is unique to a diode failure. Additionally, the efficiency of the power supply dropped by an average of 5% after the electrical overstress event occurred. The drop in efficiency is illustrated in Figure 14.

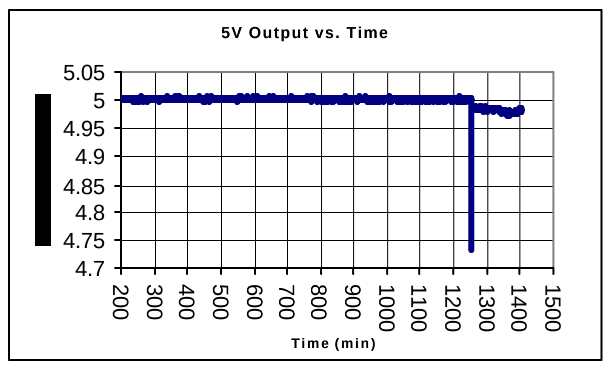


Figure 13 - 5V Output Voltage vs. Time during the Accelerated Failure Test

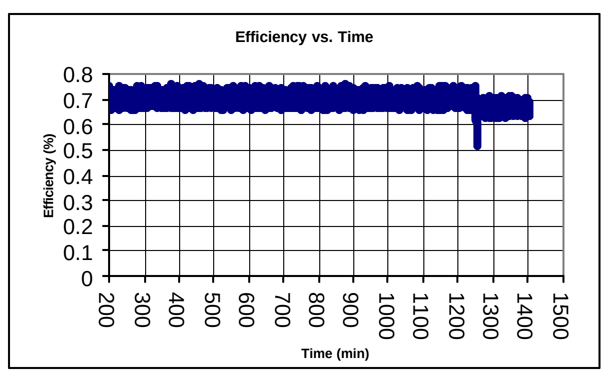


Figure 14 - Efficiency vs. Time during the Accelerated Failure Test

Indications of diode degradation are similar to the symptoms of BJT transistor degradation with one important difference. During the late stages of diode degradation, the power supply has difficulty keeping the output voltage regulated at a constant DC level. In other words, when a rectifying diode becomes damaged, the output voltage deviates from its rated value, shown in Figure 13. Therefore, as the rectifying diode accumulates damage, the following symptoms occur:

5. CONCLUSION

An integrated approach to switching mode power supply health management that implements techniques from engineering disciplines including statistical reliability modeling, damage accumulation models, physics of failure modeling, and sensor-based condition monitoring using automated reasoning algorithms has been presented. These techniques are focused on the three types of switching mode power supply components (switching transistors, filter capacitors, and rectifier diodes) that reliability studies of have shown cause the majority of failures. Novel features extracted from sensed parameters such as temperature, power quality, and efficiency were analyzed using advanced fault detection and damage accumulation algorithms. Using model-based assessments in the absence of fault indications, and updating the model-based assessments with sensed information when it becomes available provides health state awareness at any point in time. Intelligent fusion of this diagnostic information with historical component reliability statistics provides a robust health state awareness as the basis for accurate prognostic predictions. The diagnostic techniques, and prognostic models have been demonstrated through accelerated failure testing of switching mode power supplies.

BIOGRAPHY

Mr. Rolf F. Orsagh is a Project Manager at Impact Technologies with experience in the development of diagnostic/prognostic strategies for both military and industrial machinery applications. Rolf has a M.S. in Mechanical Engineering from Rochester Institute of Technology and a B.S. in Physics from Guilford College. He has been involved in developing real-time, intelligent health monitoring systems for gas turbine engines, industrial pumps, and steam turbines. Rolf has published papers in the areas of turbomachinery health monitoring, diagnostics, prognostics, and vibration control.

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